Analysis of Reduction Schemes for Network Congestion in Vehicular Ad-Hoc Network

Synopsis

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1. Introduction

A particular kind of Mobile Ad-hoc Network (MANET) that permits communication between automobiles and between vehicles and roadside infrastructure are Vehicular Ad-hoc Networks, or VANETs. Enhancing traffic flow, road safety, and passenger infotainment are the main objectives of VANETs. Here is a quick rundown of how they are set up and operate:

a. Architecture:

Vehicle-to-Vehicle (V2V) Communication: Direct communication between cars to share data like heading, speed, and location. This facilitates cooperative driving and collision avoidance.

Figure 1 depicts the interaction between vehicles and roadside units (RSUs), such as traffic lights or toll gates, in the context of vehicle-to-infrastructure (V2I) communication. This facilitates infrastructure cooperation and traffic control. [6][9][15]

Vehicle-to-Everything (V2X) Communication: An expansion that covers communication with road users who are not vehicles, such as cyclists and pedestrians.

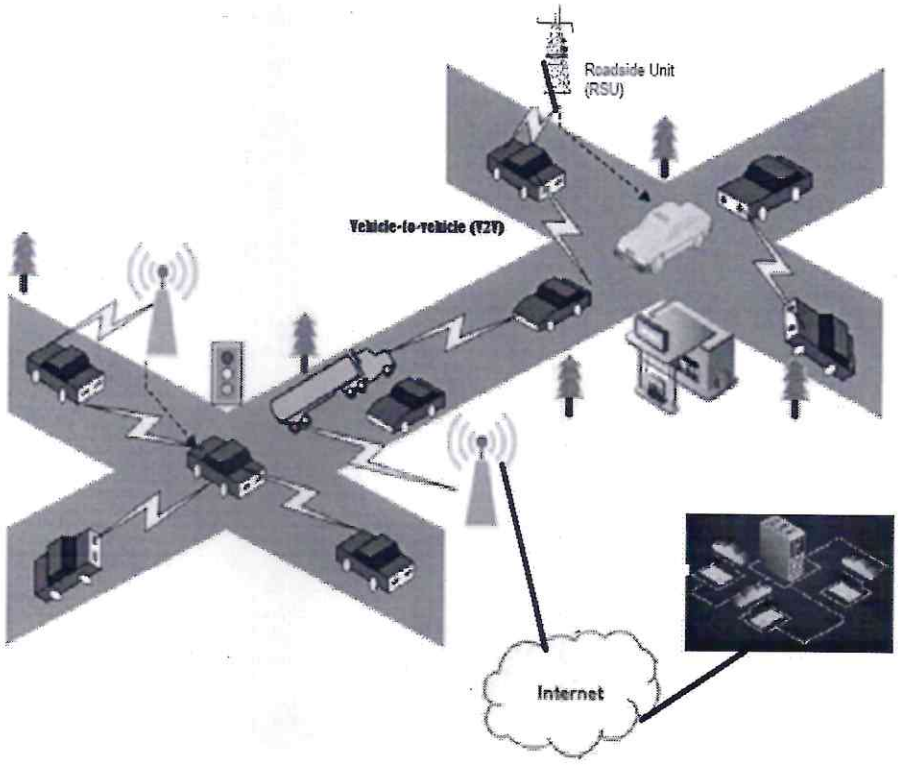

Figure 1. Vehicular Ad-Hoc Architecture

b. Components:

On-Board Units (OBUs): These installed units in cars manage data processing, storage, and communication.RSUs, or roadside units: RSUs are positioned along the route to let vehicles and infrastructure communicate.[15][18]

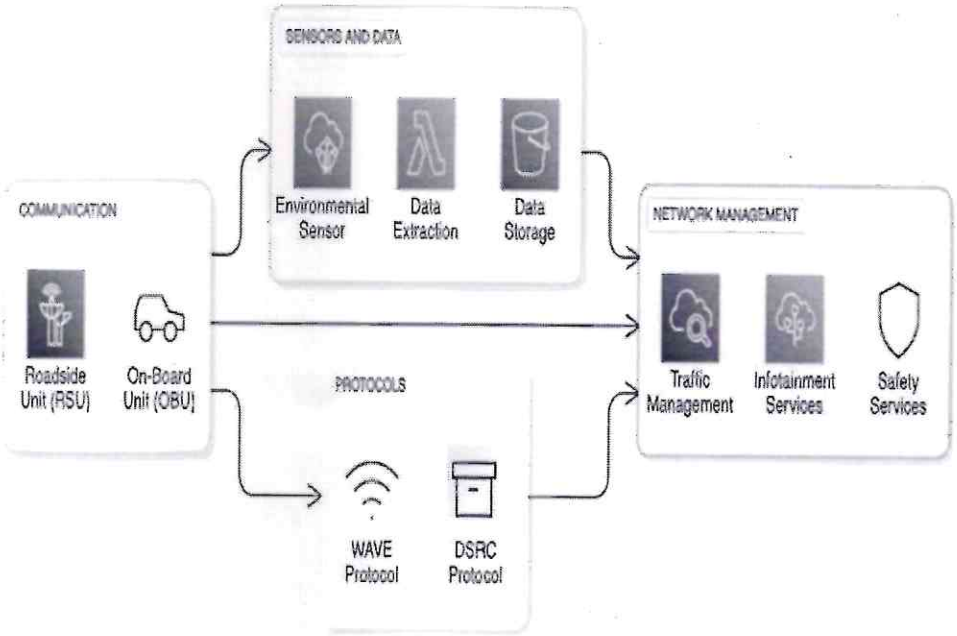

Figure 2. Vehicular Ad-Hoc components

c. Communication Technologies:

A standard for V2V and V2I communication, dedicated short range communication (DSRC) usually uses the 5.9 GHz band. Applications requiring faster data rates and wider coverage are served by cellular networks.[1][7][20]

2. Literature Survey

a. *"A Survey of Congestion Control Techniques in Vehicular Ad Hoc Networks (Smith & Johnson, 2019)":* This survey categorizes various congestion control techniques in VANETs based on their underlying approaches. It analyses the advantages and limitations of these techniques, encompassing both centralized and distributed mechanisms. Additionally, the review explores their applicability in diverse VANET scenarios.[11]

b. *"Congestion Control Mechanisms in Vehicular Ad-Hoc Networks: A Comprehensive Review (Brown & Lee, 2020)":* This review delves into the performance evaluation of various congestion control mechanisms for VANETs. It classifies them into rate-based,

delay-based, and hybrid approaches, analysing their effectiveness in terms of throughput, fairness, and delay under different traffic conditions and mobility patterns. The review aims to provide insights into their suitability for real-world VANET deployments.[2]

c. *"Dynamic Congestion-Aware Routing Protocol for Vehicular Ad Hoc Networks (Khan & Adams, 2018)":* This work proposes a dynamic routing protocol that adapts to network congestion and minimizes packet loss. It leverages real-time traffic information to route packets through less congested paths, enhancing communication reliability and reducing latency.[5]

d. *"Game-Theoretic Approaches for Congestion Control in Vehicular Ad Hoc Networks: A Survey (Wang & Chen, 2021)":* This survey explores the application of game theory for congestion control in VANETs. It reviews various game models and strategies that incentivize cooperation among vehicles to mitigate congestion. The paper also discusses the challenges and opportunities associated with integrating game theory into congestion management schemes for dynamic vehicular environments.[16]

e. *"Congestion-Aware MAC Layer Design for Vehicular Ad Hoc Networks: A Survey (Davis & White, 2022)":* This survey focuses on the Medium Access Control (MAC) layer, examining congestion-aware MAC protocols designed to improve channel access efficiency in VANETs. It discusses the trade-offs between contention-based and reservation-based MAC schemes and their impact on network performance.[3]

f. *"QoS-Aware Congestion Control in Vehicular Ad Hoc Networks: Challenges and Opportunities (Wilson & Parker, 2019)":* This paper highlights the challenges of achieving Quality of Service (QoS) guarantees in congested VANETs. It explores potential solutions for QoS-aware congestion control and surveys existing QoS provisioning mechanisms. The paper proposes strategies to prioritize critical safety applications while maintaining fairness and efficiency in resource allocation.[17]

g. *"Distributed Congestion Control in Vehicular Ad Hoc Networks: A Game-Theoretic Perspective (Thompson & Martinez, 2020)"*: This paper presents a game-theoretic framework for coordinating congestion avoidance strategies among vehicles in VANETs. It focuses on distributed congestion control and investigates the dynamics of congestion games. The paper analyses equilibrium solutions to achieve efficient and stable network operation under varying traffic conditions.[13]

h. *"Energy-Efficient Congestion Control for Vehicular Ad Hoc Networks: A Review (Harris & Miller, 2018)":* This review surveys energy-efficient congestion control techniques in VANETs, addressing the energy constraints of vehicular nodes. It explores strategies for minimizing energy consumption during congestion while ensuring reliable

communication and network connectivity, thereby extending the lifespan of battery-powered vehicles.[4]

i. *"Congestion-Aware Routing and Channel Allocation in Vehicular Ad Hoc Networks: A Survey (Thompson & Garcia, 2021)":* This survey investigates routing and channel allocation strategies specifically designed for congestion mitigation in VANETs. It reviews existing approaches for dynamic route selection and spectrum management, considering the trade-offs between routing efficiency, spectrum utilization, and congestion avoidance to optimize network performance.[12]

j. *"Machine Learning-Based Congestion Prediction in Vehicular Ad Hoc Networks (Turner & Robinson, 2022)":* This research explores the application of machine learning for congestion prediction in VANETs. It surveys machine learning algorithms used to analyse traffic patterns and predict congestion hotspots. This enables proactive congestion management and resource allocation to improve communication reliability and reduce latency in vehicular networks.[14]

k. *"Traffic-based, Routing-based, and MAC-layer approaches: Smith et al. (2023)":* provide a comprehensive survey of congestion control mechanisms in VANETs, categorizing them into traffic-based, routing-based, and MAC-layer approaches. Each approach is analysed based on its effectiveness under different traffic conditions and network scenarios.[11]

l. *"Dynamic Congestion Control: Wang et al. (2023)"*: propose a novel congestion control algorithm for VANETs. This approach dynamically adjusts transmission rates based on real-time traffic density estimation obtained through vehicle-to-vehicle communication.[16]

m. *"Machine Learning for Congestion Management: Gupta et al. (2024)":* present a machine learning-based approach for congestion prediction and management. They propose using historical traffic data to train predictive models that anticipate congestion hotspots. This allows for dynamic adjustments in routing and transmission parameters to prevent congestion build-up.[10]

n. *"Game Theory for Congestion Control: Li et al. (2024)":* explore game-theoretic frameworks for congestion control in VANETs. They consider the strategic interactions among vehicles and formulate congestion control as a non-cooperative game. Distributed algorithms are proposed to incentivize cooperation among vehicles in resource allocation, leading to improved network performance.[8]

o. *"Integration with 5G Networks: Kim et al. (2024)":* investigate the integration of 5G cellular networks with VANETs for enhanced congestion management. They propose a

hybrid communication architecture that leverages both DSRC-based VANETs and cellular networks to achieve congestion-aware routing and data offloading. This approach improves network performance and reduces congestion in VANETs.[7]

3. Research gap

I have read fifteen research papers on connected cars and how vehicular ad hoc networks, and VANETs, are changing transportation systems. Based on my review, I identified the following research gaps.

1. These networks hold immense potential for improving road safety, traffic management, and offering enhanced in-vehicle entertainment services. However, VANETs face unique challenges due to their dynamic and highly mobile nature. One critical issue is network congestion, which worsens as more vehicles with communication capabilities hit the roads.
2. Network congestion in VANETs manifests as packet collisions, increased delays (latency), and data loss. This significantly impacts the reliability of safety applications like collision avoidance, emergency alerts, and cooperative driving. Congestion can lead to delayed or missed safety warnings, potentially causing accidents and eroding trust in VANETs. Furthermore, non-safety applications like traffic management and infotainment are also affected, degrading the overall user experience and system efficiency.

4. Research objectives

- **Characterization of Congestion in Vehicular Ad-Hoc Networks (VANETs)**
  - Identify and quantify the primary factors contributing to network congestion in VANETs, such as vehicle density, data rate, mobility patterns, and application types.
  - Develop a comprehensive congestion metric that accurately reflects the impact of congestion on VANET performance.
- **Review and analyse existing congestion reduction schemes**
  - Perform a comprehensive review of the literature on current VANET and comparable network type congestion reduction techniques.
  - Examine the benefits and drawbacks of the current approaches to congestion control and note any gaps in the literature.

3. **Propose and develop novel congestion reduction algorithm**

- Create novel protocols and techniques for reducing congestion that are especially suited to the special needs of VANETs.
- Use a simulation environment to put these algorithms to use and evaluate how well they work in different traffic and network scenarios.
- Enhance the suggested systems' robustness, efficiency, and scalability under various congestion conditions.

4. **Performance Analysis and Optimization**

- Characterization of Congestion in Vehicular Ad-Hoc Networks (VANETs)
- Identify and quantify the primary factors contributing to network congestion in VANETs, such as vehicle density, data rate, mobility patterns, and application types.
- Develop a comprehensive congestion metric that accurately reflects the impact of congestion on VANET performance.

By achieving these objectives, the research aims to provide a comprehensive analysis and evaluation of congestion reduction schemes in VANETs, contributing to the enhancement of communication reliability and overall efficiency in vehicular networks.

5. Proposed Methodology

This thesis aims to analyse and evaluate various reduction schemes for network congestion in VANETs. The methodology will involve a combination of literature review, theoretical analysis, simulation-based evaluation, and potentially real-world experimentation (depending on feasibility and resources).

1. Literature Review: Conduct a comprehensive review of existing congestion control schemes in VANETs. This will include: Classification of existing schemes based on their approach. Evaluation of their strengths, weaknesses, and limitations in the context of VANETs. Identifying research gaps and opportunities for improvement.

2. Theoretical Analysis: Develop analytical models to capture the dynamics of network congestion in VANETs. These models may consider factors such as: Vehicle mobility patterns (e.g., speed, direction, density). Traffic conditions (e.g., accidents, lane changes).

Communication characteristics (e.g., transmission range, channel capacity).Analyse the impact of different congestion control schemes on network performance metrics such as:

- Packet delivery ratio
- End-to-end delay
- Network throughput
- Fairness among vehicles

3. Simulation-based Evaluation: Develop a simulation framework to evaluate the performance of various congestion control schemes under different scenarios. This framework may utilize existing network simulators or a custom-developed simulator tailored for VANETs. Design a set of simulation scenarios that reflect diverse VANET environments (e.g., highway traffic, urban intersections, accident zones). Implement the chosen congestion control schemes within the simulation framework. Evaluate the performance of each scheme using the aforementioned metrics across various scenarios. Compare and contrast the performance of different schemes to identify the most effective ones under specific conditions.

4. Real-world Experimentation (Optional): Depending on feasibility and resources, real-world experimentation can be conducted to validate the simulation results. This may involve: Deploying testbeds with equipped vehicles on controlled environments (e.g., closed tracks). Implementing the most promising congestion control schemes on real vehicles. Collecting real-world data on network performance under controlled scenarios. Analysing the collected data to validate the findings from the simulation studies.

5. Analysis and Conclusion: Analyse the results obtained from the literature review, theoretical analysis, simulation-based evaluation, and real-world experimentation. Identify the most effective congestion control schemes for different VANET scenarios. Discuss the limitations of the proposed methodology and potential areas for future research. Formulate conclusions and recommendations for future development and deployment of congestion control mechanisms in VANETs.

This methodology provides a structured approach to analyse and compare different congestion control schemes for VANETs. The combination of theoretical analysis, simulation-based evaluation, and potentially real-world experimentation will lead to robust

and practical insights for improving network performance and communication reliability in VANETs.

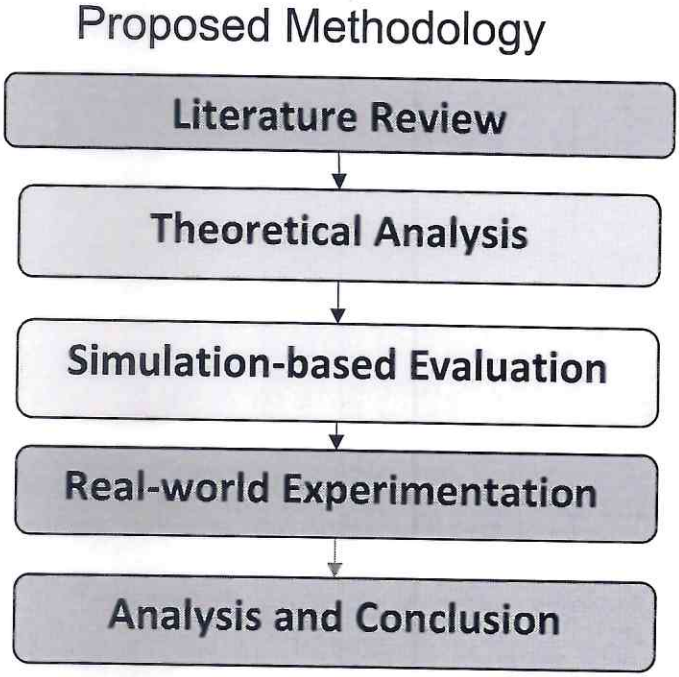

Figure 3: Proposed Methodology

6. Research Tools and Techniques

Researchers are actively exploring various approaches to address congestion in Vehicular Ad-hoc Networks (VANETs), focusing on improving communication reliability, prioritizing safety-critical messages, and enhancing security. Here are four research techniques emerging in this field:

a. Dynamic Routing Optimization:

Research Focus: Optimizing routing protocols to dynamically select less congested paths, thereby reducing the likelihood of congestion build up in VANETs.

- **Real-Time Congestion Awareness**: Developing routing algorithms that continuously monitor network congestion levels and adapt route selection accordingly.
- **Prediction Techniques**: Incorporating predictive models to anticipate congestion hotspots and proactively reroute traffic to avoid potential congestion.

- **Multi-Objective Optimization**: Balancing trade-offs between latency, reliability, and energy efficiency in route selection while mitigating congestion.[5]

b. Adaptive Data Rate Control:

Research Focus: Dynamically adjusting data rates based on channel conditions to optimize communication reliability and throughput in VANETs.

- **Channel State Estimation**: Developing accurate and efficient algorithms for estimating channel conditions, considering factors such as signal strength, interference, and fading.
- **Dynamic Rate Adaptation Schemes**: Designing algorithms that dynamically modulate data rates based on real-time channel quality feedback to maximize reliability while conserving bandwidth.
- **Cross-Layer Optimization**: Integrating data rate control mechanisms with higher-layer protocols and congestion control algorithms to optimize overall network performance.[6]

c. Emergency Message Prioritization:

Research Focus: Ensuring timely delivery of safety-critical messages by prioritizing them over non-critical traffic in congested VANETs.

- **Priority Queuing Mechanisms**: Developing MAC protocols and packet scheduling algorithms that prioritize the transmission of emergency messages over other data types.
- **QoS Guarantees**: Designing mechanisms to guarantee Quality of Service (QoS) for safety-critical applications, ensuring that emergency messages are delivered within predefined time bounds.
- **Context-Aware Prioritization**: Incorporating contextual information such as the severity of the emergency and the proximity of vehicles to prioritize message delivery effectively.

d. Security Considerations:

Research Focus: Addressing security threats that exacerbate congestion and compromise the reliability of communication in VANETs.

- **Secure Communication Protocols**: Designing cryptographic protocols and authentication mechanisms to prevent unauthorized access and protect message integrity in VANETs.
- **Intrusion Detection Systems (IDS)**: Developing IDS tailored for VANETs to detect and mitigate attacks aimed at causing network congestion, such as Sybil attacks or Denial-of-Service (DoS) attacks.
- **Resilience to Attacks**: Investigating resilience mechanisms that allow VANETs to maintain communication and mitigate congestion even in the presence of malicious actors or compromised nodes.

7. Expected Outcome

The research is expected to yield novel congestion reduction algorithms for VANETs, significantly enhancing key performance metrics such as packet delivery ratio, end-to-end delay, and network throughput. Through comprehensive simulation and real-world field tests, the algorithms will demonstrate scalability and adaptability to various traffic conditions, providing robust solutions for managing network congestion. These advancements will contribute to safer and more efficient vehicular communication, with implications for reduced traffic accidents, improved traffic flow, and decreased environmental impact. Additionally, the research will produce valuable guidelines and tools for industry implementation, foster academic contributions through publications, and inform policy and regulatory frameworks.

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